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Unveiling Climatic Trends from 1922 to 2022: A Long-Term Time-Series Analysis of Precipitation of Semi-Arid Agra District, Uttar Pradesh, India

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ABSTRACT

Background: Rainfall variation is a clear indicator of climate change. IPCC in its multiple assessment reports has raised concerns over the changing climate and rising global average temperatures which could lead to widespread and catastrophic impacts on natural and human systems. The study of long-term patterns is crucial in establishing evidence of shifting climate and informing policy decisions.
Objectives: This study examines the rainfall trend and variability of the semi-arid Agra district and assesses rainfall in the region. Annual rainfall for 101 years from 18 grid data points was statistically analysed for the same.
Methodology: For the projection and analysis of data points, a Thiessen network polygon was drawn using QGIS 3.28.4. Each grid data point was assigned a Thiessen polygon. According to the area each Thiessen polygon covers, it was assigned weights. Then according to the weight of each polygon, annual rain in that area was calculated. Next, the data were tested for homogeneity and breakpoints using the Standard Normal Homogeneity test, Buishand's Range test, Buishand's U test and Pettitt's test. After this the trend of the data was identified using Mann-Kendall and the magnitude was calculated using Theil-Sen's estimator. R-studio was used for all the statistical analysis and graph plotting.
Results: Upon conducting the Standard Normal Homogeneity test, Buishand's Range test, Buishand's U test and Pettitt's test it was found that the data was non-homogeneous with the breakpoint in the year 1967. The Mann-Kendall test revealed a declining trend in the annual rainfall and the Theil-Sen estimator calculated the magnitude of this declining trend to be -1.63 for the last century.
Conclusion: The findings suggest that climate change is having a significant impact on rainfall in the semi-arid Agra district. The declining trend in rainfall could have several negative consequences for the region, including water scarcity, crop failure, and increased risk of droughts.

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1. INTRODUCTION

The rainfall of a region is the primary indicator of its climate, as the study of precipitation patterns reveals the changing weather. Hydro-climatic research is helpful in understanding the homogeneity pattern of rainfall which is essential for the prediction of the socio-economic growth of a particular region (Xu et al., 2020). IPCC in its multiple assessment reports has raised concerns over the changing climate and rising global average temperatures. In its 5th assessment report, it stated that global temperatures are seeing a constant rise since the 19th century (IPCC, 2014). The IPCC has also warned that global temperatures will likely increase by 1.5°C above pre-industrial levels by 2040, which could lead to widespread and catastrophic impacts on natural and human systems(IPCC, 2018). It is already established knowledge that temperature change will affect precipitation (Allen & Ingram, 2002). The Clausius–Clapeyron equation states that the temperature will affect the amount of moisture the atmosphere can retain(Sánchez-Lavega et al., 2004; Trenberth et al., 2003).

Regions which are particularly susceptible to variations of precipitation are the semi-arid regions. Semi-arid regions observe a variance both spatially and temporally (Romero et al., 1998). Such regions are particularly sensitive to any variability of climate and will first experience the adverse effects of climate change(Gaur & Squires, 2018). Arid and semi-arid regions in India are widely distributed, covering about one-third of the country's land area, particularly in the northern and western parts. Studies have shown that these areas are showing an increasing trend in the frequency and magnitude of extreme rainfall events and the areas categorised under the arid and semi-arid category are increasing(Kesava Rao et al., 2013). These regions are home to unique ecosystems, and their sensitivity to environmental changes is increasingly becoming a concern due to factors such as global climate change and rapid economic growth. To address such issues, the Indian government has implemented various ecological restoration programs since the early 2000s, such as the "National Afforestation Programme" launched in 2002 and the "National Agroforestry and Bamboo Mission" launched in 2006-2007. These programs aim to restore degraded land, promote afforestation, and improve human and natural relationships. Consequently, the arid and semi-arid regions of India have become subject to significant interest for research on climate change, land cover change, and the relationship between climate and vegetation.

A look towards the future shows uncertainty concerning climate variability, and extreme precipitation events will rise. It is estimated that such events will significantly increase in India between 2020 to 2100 (Singh & Chudasama, 2021). Therefore, it is important to study long-term climate records to understand the climate change pattern and to predict future trends (Houghton et al., 1990). In recent years large volumes of historical records have become easily accessible (Wang et al., 2016).

In light of the above concerns and developments, this paper aims to analyse the long-term rainfall patterns of the semi-arid Agra district. With long-term analysis of precipitation data, the trend of rainfall can be understood. The result of this analysis will be helpful in investigating the impact of climate change at a local level so that in future, predictions can be made and policies can be adopted for better preparedness against such changes.

2. METHODOLOGY

Graphical abstract of the methodology adopted in the paper with major steps is shown in Fig.1:

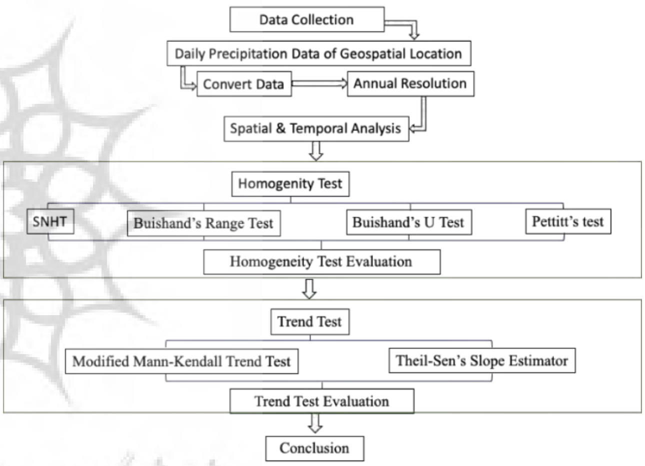

Fig 1. Graphical abstract of the methodology adopted in the paper with major steps

2.1. Selection of Study Area

Agra district, one of 75 districts of Uttar Pradesh, a state in northern India was selected for this study (Figure 2). Uttar Pradesh is the most populous state of India with a land area of 2,43,286 sq. km. and a population of over 241 million (Up.Gov.In, n.d.). Agra City of Agra district is a historical city of international importance and has a population of 4.42 million (2011 Census). The city is subject to rapid urbanisation and commercial activities (Gardner et al., 2016). Agra district consists of 6 tehsils (Agra, Etmadpur, Kiaroli, Khairaghar, Fatehabad, Bah) and is located between the latitudes 26.74° to 27.71° and 77.41° and 78.84° longitude. The district spreads across an area of 10,863 sq. Km. which is drained by the river Yamuna. Agra has a semi-arid climate and receives a monsoonal annual rainfall of 663.8 mm (Asati, 2012), mostly between June and September (Gardner & Biswas, 2015). The southwest monsoon and western disturbance bring moisture to northern India, and Agra receives its share of precipitation.

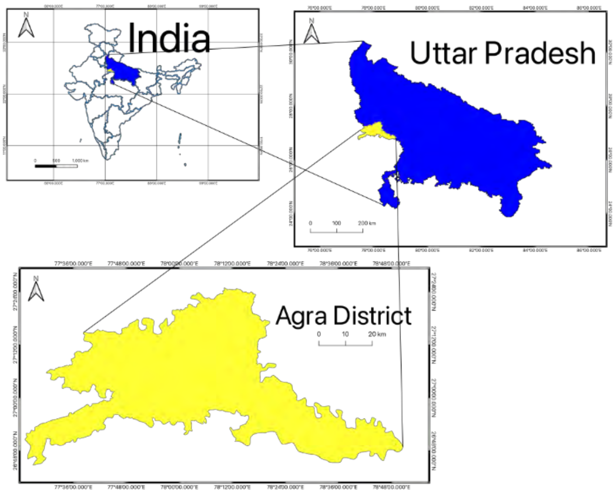

Fig 2. Study area

2.2. Data collection and processing

Since the assessment of climate requires analysis of weather parameters for an extended period, rainfall data was used for 101 years starting from 1922 till 2022. The rainfall data was downloaded from the Indian Meteorological Department servers using the 'imdlib' python library (Nandi & Patel, 2020). The grid data was in binary format and is available at 0.25-degree resolution for rainfall (Gardner, n.d.). At 0.25 degrees, data from 18 grid points was obtained (Figure 3). The administrative division's shape file of the region was obtained from Survey of India.

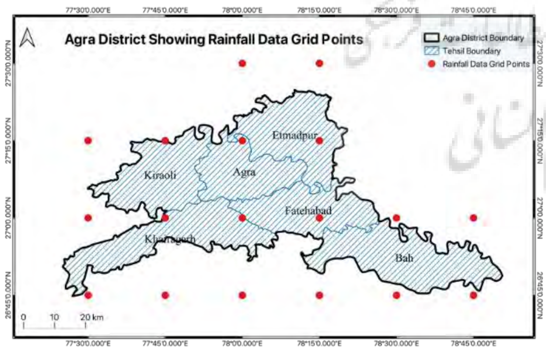

Fig 3. Map of Agra district along with grid points of which data is analysed in this study

2.3. Methodology

After obtaining the daily precipitation data it was converted to annual format using Microsoft Excel. For the projection and analysis of data points, a Thiessen network polygon was drawn using QGIS 3.28.4. Each grid data point was assigned a Thiessen polygon (Figure 4). According to the area each Thiessen polygon covers, it was assigned weights (Table 1). Then according to the weight of each polygon, annual rain in that area was calculated.

Next, the data were tested for homogeneity and breakpoints using the Standard Normal Homogeneity test, Buishand's Range test, Buishand's U test and Pettitt's test. After this the trend of the data was identified using Mann-Kendall and the magnitude was calculated using Theil-Sen's estimator. R-studio was used for all the statistical analysis and graph plotting.

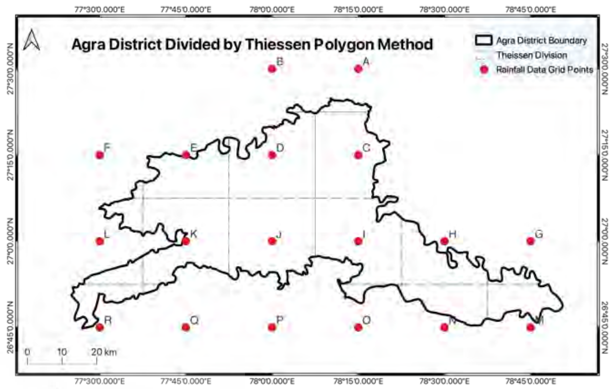

Fig 4. Agra district with Thiessen polygons

Table 1. Data grid points from A to R with Latitude, Longitude, Area and Weight assigned

Grid point	Long.	Lat.	Area(sq. km.)	Weight
A	78.25	27.5	42.03	0.009867
B	78	27.5	7.48	0.001756
C	78.25	27.25	482.12	0.113179
D	78	27.25	537.77	0.126243
E	77.75	27.25	340.87	0.08002
F	77.5	27.25	13.4	0.003146
G	78.75	27	48.11	0.011294
H	78.5	27	300.56	0.070557
I	78.25	27	563.19	0.13221
J	78	27	598.3	0.140453
K	77.75	27	541.41	0.127098
L	77.5	27	170.27	0.039971
M	78.75	26.75	193.51	0.045427
N	78.5	26.75	233.9	0.054909
O	78.25	26.75	39.48	0.009268
P	78	26.75	1.56	0.000366
Q	77.75	26.75	10.53	0.002472
R	77.5	26.75	135.31	0.031764
			4259.8	1

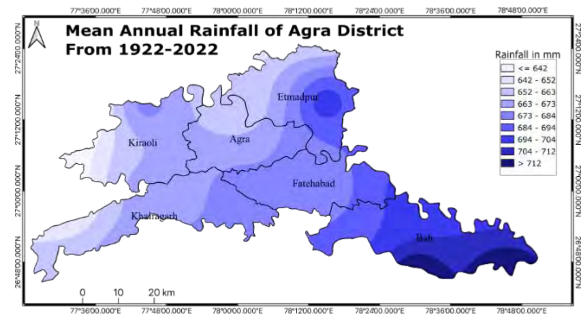

Fig 5. Mean Annual Rainfall of Agra District from year 1922 to 2022

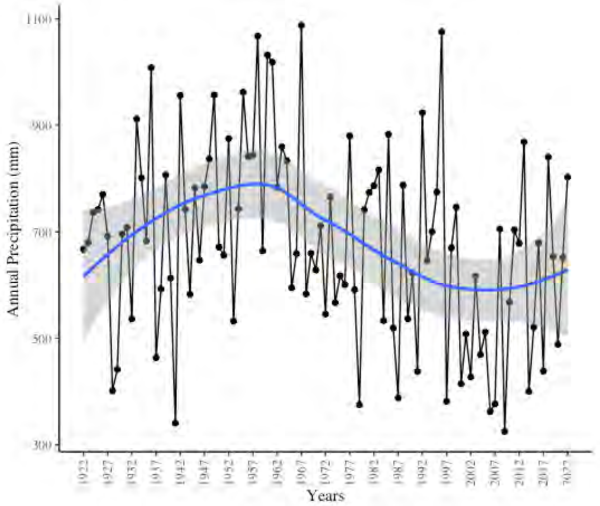

Fig 6. Years and Annual Precipitation are shown with black dots. The blue line represents the linear regression i.e. the estimated relationship between years and annual precipitation. The default confidence level of 95% (in the geom_smooth function in the ggploy2) suggests a high degree of confidence in the line's fit to the data. The shaded grey region around the line indicates the confidence interval, representing the uncertainty associated with the estimated relationship.

3. Homogeneity test and change point detection

For precise assessment of climate variables there should be consistency in data as inhomogeneous data is not reliable for statistical analysis (Bickici Arikan & Kahya, 2019; Eischeid et al., 1995).
Homogeneity analysis was conducted, and the breakpoint of the precipitation time series data was calculated using the Standard Normal Homogeneity test (Alexandersson, 1986), Buishand's Range test, Buishand's U test (Buishand, 1982) and Pettitt's test (Wijngaard et al., 2003) as these tests are standard and commonly used for time series analysis (Mohammed & Scholz, 2023).

3.1. Results of homogeneity tests

3.1.1. Standard normal homogeneity test

The standard normal homogeneity test was applied to the 101 years' precipitation data series of the Agra district. At a 5% significance level, the p-value turned out to be 0.0073 which was less than 0.05. Therefore, the null hypothesis can be rejected, and it can be concluded that there is evidence of a structural break in the data. The alternate hypothesis states that the true change point (delta) is not equal to zero, suggesting the presence of a significant change in the rainfall pattern.

3.1.2. Buishand's Range Test

The Buishand Range Test is a parametric test that detects multiple change points in a time series. It uses a likelihood ratio approach to estimate the change points based on the ranges of data segments. The test statistic compares the observed range with the expected range under the assumption of no change points. A p-value is obtained to determine the significance of the change points. The result of the test suggests a change point in the data set in the year 1967. The test statistic, R/sqrt(n), was calculated to be 1.9105 and the p-value was 0.007, suggesting the change point in the data.

3.1.3. Buishand's U Test

The non-parametric Buishand's U test detects a single change point in the time series by comparing the ranks of the data points before and after a potential change point to determine if there is a significant difference.
The test results stated that the p-value was at a significant level below 0.05, i.e., 0.0035, suggesting that the observed change point is statistically significant. The shift in the rainfall data occurred in the year 1967.

3.1.4. Pettitt's test

Another non-parametric test used frequently in hydro-climatological studies, to detect a single change point in time series data is Pettitt's test (Mallakpour & Villarini, 2016; Xie et al., 2014). It determines the points at which the maximum difference between two cumulative sums of data occur. The two-sided test helps in the detection of change in either direction (negative or positive), whether there is an increase or a decrease in the rainfall.
The two-sided hypothesis of the test suggested that the true change point in the data is not equal to zero. The calculated p-value of the data is 0.0073 which is less than the significance level of 0.05. This suggests a probable change at point K which was the year 1967 out of 101 years. Further the test statistic value U* which suggests the deviation from the null hypothesis was 986, suggesting strong evidence in favour of the alternate hypothesis.

4. Trend detection

The non-parametric Mann-Kendall and Theil-Sen estimators are commonly used to analyse the trend of time series data (Diop et al., 2016). These are distribution-free tests and do not require normally distributed data. The Modified Mann-Kendall was used to determine the trends in the data and the Theil-Sen's slope was used to find out the exact magnitude of this change.

4.1. Modified Mann-Kendall test

The Mann-Kendall non-parametric test is commonly used to identify trends in climate data. This statistical method is specifically designed to detect monotonic trends, which are patterns where there is a consistent increase or decrease in values over time (Pohlert, 2020). This test can determine whether there is a statistically significant trend in the data and give a better insight in the patterns and changes that are occurring in the climate.

The Modified Mann-Kendall trend test was utilized to identify trends in time-series data of rainfall. This test expands upon the original Mann-Kendall test by taking into account the possibility of dependent observations within the time series, unlike the traditional version which assumes each observation is independent (Hamed & Ramachandra Rao, 1998). Compared to the traditional Mann-Kendall test, the Modified Mann-Kendall test can more accurately determine the presence and magnitude of trends in data. The modification involves adjusting the test statistic and critical values to account for the presence of autocorrelation, thereby reducing the risk of false positives or negatives. Autocorrelation occurs when the values of a variable in a time series are correlated with previous values of the same variable (Hamed & Ramachandra Rao, 1998).

4.2. Theil-Sen Slope

The next step in the methodology is to measure the trend in the rainfall data using the Theil-Sen estimator. The Theil-Sen estimator is preferred over the simple linear regression method as it uses the median method (Figure 7), therefore, it is robust to the outliner (Theil-Sen | Open Mind, n.d.). If a slope i.e., change per unit time, is present then it can be estimated with the help of a non-parametric method of Theil and Sen (Partal & Kahya, 2006).

4.3. Result of trend detection test

On conducting the Modified Mann Kendal trend test on the data for 101 years for the duration 1922 to 2022 the following results were achieved. The entire area of the Agra district showed a declining trend in annual rainfall. The year 1967 received the maximum annual rainfall (1088 mm), while the year 2009 received the lowest (324 mm) during the study period. Normalised Kendal Tau which measures the strength and direction of the trend was found to be -0.163, this indicates a weak negative trend in the annual rainfall. The p-value associated with Kendall's tau was 0.04 suggesting that the null hypothesis of no trend can be rejected and the alternative hypothesis which suggests a trend can be accepted. The Z statistic which measures the deviation of the observed Kendall's tau from its expected value was -2.051.

The general trend of rainfall for the district is negative for the entire assessment period of 101 years. The slope value for the study area was -1.63. This slope is graphically depicted in Figure 7 while Figure 8 shows the trend for all the different data points in the Agra district plotted spatially.

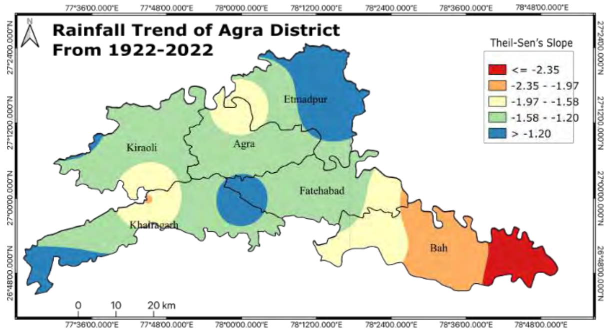

Fig 7. Rainfall trend of Agra district for all the data points calculated using the Theil-Sen's Slope

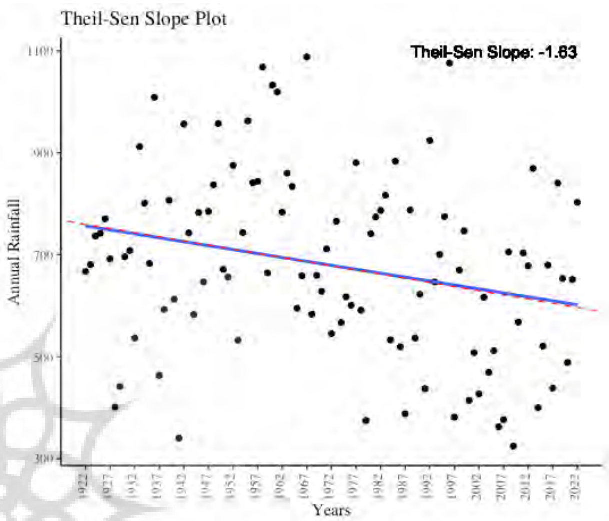

Fig 8. In the plot black dots show the data point, while the blue line shows the regression line (a non-robust ordinary least squares method). It is compared to the red dashed line representing the Theil-Sen Slope (a robust estimate). The plot gives a visual idea of decreasing trend of rainfall over the years.

5. CONCLUSION

This study was undertaken to find a long-term pattern of rainfall in the semi-arid Agra district. All the tests were conducted at a 95% confidence level. Upon analysing the data of 18 data points for 101 years (1922-2022) it was found that the mean annual rainfall of Agra district was 671 mm. This mean varied for different tehsils, the range was from 642 mm to 712 mm for different parts (Figure 5). The district receives the majority of this rainfall during the monsoon months i.e. June to September, which averages around 603 mm. There is a visible increase in the annual mean rainfall as one moves west to east and from north to south. Usually, tehsils Bah, Fatehabad and Etmadpur received more rainfall than Kiraoli, Khairagarh and Agra. Next for visual interpretation Figure 6 shows the dependent variable on Y-axis i.e., 'Annual Precipitation (mm)' plotted against the independent variable on X-axis i.e., 'Years'. The smooth linear regression line in blue shows the linear relationship between time and precipitation while the grey band is the confidence interval at 95%. On seeing the annual data along with the curve, it can be said that there is a cyclic behaviour as we can see a peak and trough. Also, there is a certain seasonality in the data every 5-7 years. This trend needs further statistical assessment.

The Modified Mann-Kendall test revealed evidence of a negative trend in the data. Figure 8 shows a weak downward trend of rainfall during the last 101 years at a magnitude of -1.63. The magnitude of the decrease in rainfall varies from -1.20 to -2.35 and regions on the east of the study area have a higher magnitude of downward trend than those on the west. While most of the central region falls between -1.20 to -1.58.

The findings suggest that climate change is having a significant impact on rainfall in the semi-arid Agra district. The declining trend in rainfall could have several negative consequences for the region, including water scarcity, crop failure, and increased risk of droughts. There is a need for further research on the impact of climate change on rainfall in the region and for the development of adaptation strategies to mitigate the negative impacts of climate change.

This study also serves as a reference for future climate change studies and sustainable development policy decisions for the semi-arid Agra district facing a decline in rainfall. After studying the seasonality of the data we can also predict future rainfall scenarios in the region. The non-homogeneous pattern in the precipitation data may be due to global climatic patterns. Further analysis of rainfall along with El Niño patterns may help us understand the regional patterns of rainfall better.

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